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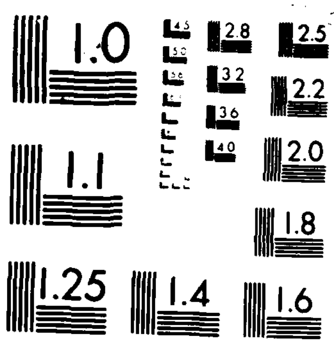

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STUDY OF THE B_S TEMPERATURE IN A MOLYBDENUM-CONTAINING ULTRA-LOW CARBON BAINITIC STEEL FOR HEAVY PLATE APPLICATIONS

by

C.I. Garcia and A.J. DeArdo

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The bainite transformation start temperature B_S, has been studied in a series of modified ultra low-carbon bainitic (ULCB) steels. The influence of variables such as composition, thermomechanical processing, cooling rate and reheating temperature has been assessed in terms of their respective effects on the B_S temperature of ULCB steels. The results of this study have shown that the B_S temperature is strongly influenced by both the microstructural state of the austenite and the cooling rate for a given set of compositions and thermomechanical processes.

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Study of the B_S Temperature in a Molybdenum - Containing Ultra-Low Carbon Bainitic Steels for Heavy Plate Applications

C. I. Garcia and A. J. DeArdo

ABSTRACT

The bainite transformation start temperature B_S, has been studied in a series of modified ultra low-carbon bainitic (ULCB) steels. The influence of variables such as composition, thermomechanical processing, cooling rate and reheating temperature has been assessed in terms of their respective effects on the B_S temperature of ULCB steels. The results of this study have shown that the B_S temperature is strongly influenced by both the microstructural state of the austenite and the cooling rate for a given set of compositions and thermomechanical processes.

$$B_S(^oC)=830-270(\%C)-90(\%Mn)-37(\%Ni)-70(\%Cr)-83(\%Mo) \quad \text{--- (1)}$$

$$B_{50}(^oC)=B_S-60 \quad \text{--- (2)}$$

$$B_f(^oC)=B_S-120 \quad \text{--- (3)}$$

these equations were obtained by using the least squares method in a series of steels with compositions (wt%) ranging as follows:

Carbon	0.1 - 0.55
Manganese	0.2 - 1.70
Nickel	traces - 5.00
Chromium	traces - 3.50
Molybdenum	traces - 1.00

the B_S temperature in this study [7] was determined from isothermal transformation experiments. This B_S temperature is defined as the temperature above which bainite will not form. Pickering [4] combined the results obtained from the above equations and the results shown in figure 1 to obtain an equation that enable the calculation of the tensile strength of the steel for a given composition.

$$U.T.S.(MPa)=15.4[16+125(\%C)+15(\%Mn+\%Cr)+12(\%Mo)+6(\%W)+ 8(\%Ni)+4(\%Cu)+25(\%V+\%Ti)] \quad \text{---(4)}$$

The bainitic steels investigated by Pickering showed that the yield stress varies with respect to the tensile strength as follows:[8]

$$0.2\%YS(MPa)=(0.67\sim0.55)UTS(MPa) \quad \text{for } UTS \geq 1000$$

$$0.2\%YS(MPa)=(0.70\sim0.75)UTS(MPa) \quad \text{for } UTS \leq 500 \quad \text{--- (5)}$$

The above discussion of the evaluation of the linear equations developed by Pickering et al., [2-4] and the other workers [5-7] warrants the re-evaluation of these relationships for ultra-low carbon bainitic steels. That is, most of the

INTRODUCTION

A series of modified ultra low-carbon bainitic (ULCB) steels is being investigated as possible candidates to substitute for conventional quenched plus tempered (Q + T) high yield strength steels.[1] One of the major attractions of ULCB steels over Q + T steels is that, ULCB steels are capable to attain a good combination of mechanical properties in the as-hot rolled condition in sections up to 100 mm (4 in.) thick, without the need of additional heat treatment. Another major advantage of ULCB steels over Q + T steels is the weldability behavior. Because it is well known that both the overall weldability and weldment toughness are inversely related to carbon-equivalent values, especially at high carbon contents, the weldability of the Q + T high yield strength steels is relatively poor. Since ULCB steels can develop high strength and toughness with low carbon content, these steels should exhibit good weldability and HAZ toughness.

In spite of the very encouraging preliminary results obtained to date [1], the full potential of these modified ULCB steels is yet to be realized. That is, in order to optimize these steels, a more fundamental understanding of the several factors that influence the microstructural and mechanical behavior of these ULCB steels needs to be developed. For example, the combined or individual assessment of factors such as, composition, austenite grain coarsening behavior, austenite conditioning, and thermomechanical history on the bainite transformation start temperature, B_S, is of primary importance. The importance of the B_S temperature in ULCB steels is obvious, because their strength is strongly related to their bainite transformation start temperature.

Since most of the work published in the literature [2-7] concerning the relationships between composition and B_S, strength and B_S, and strength and relationships published in the literature [2-7] have been obtained from steels containing relatively high carbon content and they did not take into account the influence of Nb content and austenite deformation on B_S temperature.

EXPERIMENTAL PROCEDURE

A series of molybdenum-containing ultra-low carbon bainitic steels were studied. The chemical composition (in wt%) of the steels evaluated in this investigation are shown in Table I. The steels were vacuum melted in an induction furnace. The ingot weight and size was 225 kgs (500 lb) and 200mm X 200mm X 675mm (8 in. X 8 in. X 27 in.), respectively. These ingots were reheated to 1150°C (2120°F) and deformed 50%, then air cooled to room temperature. The slabs with cross section of 140mm X 140mm (5.5 in. X 5.5 in.) were reheated to 1100°C (2012°F) and rolled between 850-775°C (1562-1427°F) to a final thickness of 25.4 mm (1 in.). The as hot rolled strength from the plates was measured using standard procedures. In addition, since it was not possible to obtain cooling charts from the plates, the B_S temperature for the steels used in this investigation was determined from specimens reheated for 1 hour at 1100°C (2012°F) and controlled cooled. The mean cooling rate between 750 and 650°C (1382-1202°F) was 0.38°C/sec (0.68°F/sec). This cooling rate simulates the cooling rate of 25.4mm (1 in.) thick plate under air cooling conditions. It is important to mention, that in this investigation the B_S temperature is defined as the temperature at which a thermal arrest appeared in the cooling curve. According with Coldren et al., this B_S temperature corresponds to the temperature for approximately 15% bainitic transformation[5,6].

In future work, precautions have been taken so cooling curves from the actual hot rolled plates can be obtained. This procedure will provide us with a more accurate analysis of B_S and strength relationships. In order to study the influence of reheating temperature and cooling rate on the B_S temperature a series of experiments were conducted. Three reheating temperatures were selected,

BACKGROUND

It has been well established that as the temperature of the bainite formation is decreased, the resulting substructure is greatly refined. In addition, it is well known that the finer and denser the substructure of a bainitic steel, the higher the corresponding yield and tensile strengths of the steel. Irvine and Pickering [2-4] have shown that in the absence of any precipation hardening, the effect of solid solution could be disregarded, hence the relationship between the strengths and the transformation temperature of the steel is linear, figure 1. However, since for a given composition and cooling rate, the bainitic reaction occurs over a temperature range, it is necessary to specify a parameter to which the term transformation temperature can be applied. Irvine and Pickering defined the transformation temperature of continuously cooled steels as the temperature for 50% transformation (B_{50}).

Other workers [5,6] have also found linear relationships between strength and B_S temperature, regardless of whether the B_S temperature was varied by changes in chemical composition or cooling rate (Fig 2). Coldren et, al. [5,6] defined the B_S temperature of continuously cooled steels as the temperature at which an upward deviation from a Newtonian cooling curve is first observed. This behavior is called thermal arrest. A comparison of B_S temperatures determined from cooling curves and from dilatometric transformation studies, revealed that the B_S temperature observed from the cooling curves corresponded to a 15% transformation [5]. Therefore, special care must be taken not to confuse the B_S temperature from Coldren et al.,[5,6] with the B_S temperature often presented on transformation diagrams for the 1% transformation line.

Studies by Steven and Haynes between chemical composition and the B_S temperature resulted in the following equations [7] composition has been done for bainitic steels with carbon contents $\geq .1$ wt% and no Nb additions, a re-evaluation of the aforementioned relationships for the modified ULCB steels is necessary. In addition, the influence of austenite conditioning on the B_S temperature should also be considered.

The major objective of this report is to present a summary of the results of an ongoing investigation directed to assess the influence of composition, thermomechanical processing cooling rate and reheating temperature on the B_S temperature of the modified ULCB steels.

Coldren's work the strength increases at the rate of about 1 ksi per 3.66°C decrease in B_S temperature, whereas in the ULCB steels the strength increases about 1 ksi per 2.2°C decrease in B_S. A possible explanation for the difference in the slopes of the lines shown in Figure 5 is that, in Coldren's experiments the decrease in B_S temperatures was done by increasing the cooling rates, while maintaining compositional variations to a minimum. In our studies, the changes in B_S temperature where achieved through variations in alloy composition, hence ULCB steels are expected to have higher strength via solid solution effects.

It is well known (8) that in order to have bainitic steel plates with a wide range of section sizes with the least possible variation in microstructures and properties, the bainite transformation C- curve should have a flat top. Experiments directed to have an idea about the shape of the bainite transformation C- curve for the ULCB steels used in this investigation were done. The results of the influence of cooling rate on the B_S temperature of these steels are show in Table II. These results indicate that the B_S temperature is dependent on the cooling rate for a given ULCB steel composition.

The effect of reheating temperature on the B_S temperature of a given ULCB steel is illustrated in Table III. The results from this table show that when reheating is done below the T_{GC} and dissolution temperature (T_{DS}), the onset of the B_S temperature is increased. On the other hand if the reheating is done above the T_{GC} and T_{DS} only slight changes on the onset of the B_S temperature are observed. For example, for steels 2 and 8 containing 0.05% Nb, it is expected that on reheating these steels at 1100°C most of the Nb will be in solution. Hence, the changes in B_S temperature observed after reheating at 950°C suggest that the extent of the amount of Nb in solid solution strongly influences the onset of ther B_S temperature. That is, the larger the amount of Nb in solution the lower the B_S temperature. Compare B_S temperature for steels 8 and 9 after reheating at 1100°C

Figure 5 shows a comparison of the calculated and measured strengths and B_S temperatures for steels 2, 3, 11, 12 and 13. The calculated strengths and B_S temperatures were obtained using eqns. 1 and 4. The results from Figure 5 show a large difference between the calculated and measured value of strength and B_S temperatures. A major reason for the observed difference in these values is that ULCB steels have a niobium, boron and very low-carbon additions. In general, ULCB steels have amore complex chemistry than those steels used to elaborate eqns. 1 thru 5.

In Figure 5 has also been superimposed data from Pickering, and from Coldren studies. When comparing the data shown in Figure 5, it is important to remember that the strength values from Pickering data correspond to 50% transformation, while the data from Coldren and from our studies are for 15% transformation. The data from Pickering cannot accurately be extrapolated to strength values corresponding to 15% transformation, because the percent of transformation is not a linear function of the temperature. In addition, to the differences in strength between the calculated and measured values for a given B_S temperature, the ratio of yield stess (0.2% offset) to tensile strength is significantly different for the steels studied by Pickering et. al., and by Coldren et. al., when compared to the ULCB steels used in this investigation. For example, in Pickering results the ratio YS/TS was about 0.6, where in Coldren's was about 0.75. Coldren found a YS/TS ratio of about 0.6 whenever martensite-austenite constituent was present, Figure 6. In our studies the YS/TS ratio was in the range of 0.81 - 0.90. These results indicate that the yield and tensile results for a ULCB steel cannot be adequately represented with a equation of the form shown in eqn. 5.

A comparison of strength results from Coldren [5,6] and this study, revealed that the ULCB steels have higher strength for a given B_S temperatrue, see Figure 5. Another significant difference is the slope of the lines. That is, in

950, 1100 and 1250°C (1742, 2012 and 2282°F). These temperatures correspond to conditions below the grain coarsening temperature (T_{GC}), just about the T_{GC} and above the T_{GC}. In addition, mean cooling rates of 1.86°C/sec, 0.97°C/sec and 0.38°C/sec in the temperature range of 750-650°C were used for each of the above reheating conditions. The size of the specimens used was approximately 25.4mm X 25.4mm X 25.4mm (1 in. X 1 in. X 1 in.). Center hole thermocouples were machined in each specimen. This procedure allows the insertion of thermocouples to monitor the heating and cooling cycles in the samples.

The influence of thermomechanical treatment on the B_S temperature was done using cylindrical specimens with size of 19mm (.75 in.) in diameter, 28.6mm (1.125 in.) in height. These cylinders were prepared from the steel plates in the as hot-rolled condition. Prior to the machining of the specimens, the steel plates were reheated for 1 hour at 1100°C (2012°F) and then water quenched. The B_S temperature was determined for the following conditions; underformed, 20% and 51% deformation. The specimens deformed 20% were tested at 800°C with a single hit. The specimens deformed 51% were done in two hits, 30% deformation at 850°C and 30% at 800°C. The strain rate used was 1 sec^{-1}. After deformation the specimens were controlled cooled in the temperature range 750°C and 650°C at a mean rate of 1.5 °C/sec. A schematic representation of the aforementioned deformation schedules is shown in Figure 3. All the tests were performed in a modified MTS hot deformation machine.

RESULTS AND DISCUSSION

The results between strength and B_S temperature determined from the simulated cooling rate for the 25.4 mm (1 in) plates are shown in Figure 4. The results from this figure revealed that there is a good linear relation betweeen the measured strength and the measured B_S temperature.

and 1250°C. These two steels have similar composition, the difference is the Nb content, steel 8 has 0.05% and steel 9 has 0.10%. The B_S temperature in steel 8 after reheating at 1100°C and 1250°C did not change, whereas the B_S temperature for steel 9 showed a shift at 12°C for the two reheating temperatures.

In Figure 7 is shown the relation between calculated B_S temperature (using eqn. 1) and the measured B_S temperature for continuously cooled samples. The cooling rate was 1.8°C/sec. The results from Figure 7 can be used to assess the influence of Nb and B on the B_S temperature. For example, steels 2a, 8 and 9 have the same base composition so calculated B_S temperatures are nearly the same but measured B_S temperatures are quite different. The major difference in composition between steels 2a and 8 is the B content, and between 8 and 9 is the Nb content. The above results clearly indicate that eqn. 1 needs to be re-evaluated for ULCB steels.

The influence of thermomechanical processing on the B_S temperature is shown in Table IV. The steels used in this experiment were choosen for two reasons; first, the cover a wide range of B_S temperatures and second, these steels should not exhibit any ferrite precipitation prior to bainite transformation after large amounts of austenite deformation. The results from Table IV indicate that steels with high B_S temperature (as measured prior to any deformation), tend to show an increase in the B_S temperature with amount of deformation. However, steels that have low B_S temperature (w/o deformation), display a lowering of the B_S temperature with increasing the amount of austenite deformation. The microsctructure behavior of bainite from the above thermomechanical treatment is shown in Figure 8A and 8B.

A possible explanation of the aforementioned phenomena is when steels with low B_S temperature are heavily thermomechanically treated, the austenite lattice is severally deformed. So, to maintain the lattice correspondence and semi-coherent interface during martensitic (bainitic) transformation is difficult. Hence, the bainitic transformation from a heavily deformed austenite is shifted to lower temperatures. On the other hand, in steels with high B_S temperature the influence of austenite deformation facilitates the bainitic transformation. That is, when bainitic transformation takes place at high temperatures diffusion events are more important. In the case of a steel with a deformed austenite, the condition of the austenite will enhance the diffusion processes. Therefore, steels with high B_S temperatures transform at even higher temperatures as the amount of deformation increases.

CONCLUSIONS

The results obtained in this study have clearly indicated that:

- There is a linear relationship between the yield stress, tensile strength and the B_S temperature of an undeformed austenite.

- In lean steel compositions B_S temperature is strongly related to cooling rate. In heavily alloyed steels B_S temperature is almost independent of cooling rate.

- The amount of Nb and B in solution strongly affects the B_S temperature. That is, the higher the amount of these elements in solution the lower the B_S temperature and viceversa.

- The role of austenite deformation on the B_S temperature of ULCB steels is: steels with high B_S temperature tend to exhibit even higher B_S temperatures as the amount of deformation increases. The opposite is true for steels with low B_S temperatures.

TABLE II

INFLUENCE OF THE COOLING RATE ON B_s
(Reheat temperature 1100°C)

Steel	B_s(°C) (a)	(b)	(c)
2a	581	597	586
2	497	503	502
3	531	534	541
11	559	560	584
12	539	546	561
13	489	487	492

Cooling rate between 750 and 650°C:
(a) 1.86°C/sec.
(b) 0.97°C/sec.
(c) 0.38°C/sec.

TABLE I

CHEMICAL COMPOSITION (wt%) OF STEELS INVESTIGATED

Steel	C	Mn	Ni	Mo	Cr	Ti	Nb	N	B
6	.02	1.98	--	--	--	.013	.05	.004	.001
7	.02	.97	.50	.50	--	.016	.05	.005	.001
8	.02	.97	1.00	.97	--	.014	.05	.004	.001
9	.02	.96	.98	.98	--	.014	.10	.004	.001
1	.018	.98	.53	.52	--	.012	.046	.0059	.0008
2a	.018	.93	1.03	.97	--	.011	.051	.0055	.0004
2	.017	1.01	3.15	3.02	--	.013	.055	.001	.0011
3	.018	.98	2.03	1.95	--	.016	.054	.0008	.0013
10	.025	.90	--	.50	.71	.014	.046	.006	.001
11	.021	.94	--	.98	1.33	.014	.049	.006	.001
12	.021	.99	1.41	1.49	--	.016	.052	.006	.001
13	.028	.91	2.69	3.01	--	.014	.051	.006	.001
4	.019	.51	3.05	1.53	--	.021	--	.007	.001

Other Elements: $P < .005$; Si - 0.20

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TABLE III

INFLUENCE OF THE REHEAT TEMPERATURE ON B_s FOR COOLING RATE BETWEEN 750 AND 650°C - 1.86°C/sec.

Steel	Reheat temp. (°C)	B_s(°C)	ΔT
2	950 1100 1250	518 497 499	21 -2
8	950 1100 1250	567 559 559	8 0
9	950 1100 1250	571 548 536	23 12

TABLE IV

Measured B_s(°C) after 0%, 20% and 50% Deformation

Steel	Deformation				
	0%	20%	50%	$B_{s(20)}-B_{s(0)}$	$B_{s(50)}-B_{s(0)}$
6	632.5	647.5	658.5	15	26
2a	589.5	607.5	614.0	18	24.5
3	539.5	552.5	551.5	13	12
2	503.5	496.5	493.0	-7	-10.5
13	490.0	489.5	493.5	-0.5	3.5
4	564	562	568.5	-2	4.5

Re-heat 1100°C
Cooling rate between 750°C and 650°C - 1.5°C/sec.

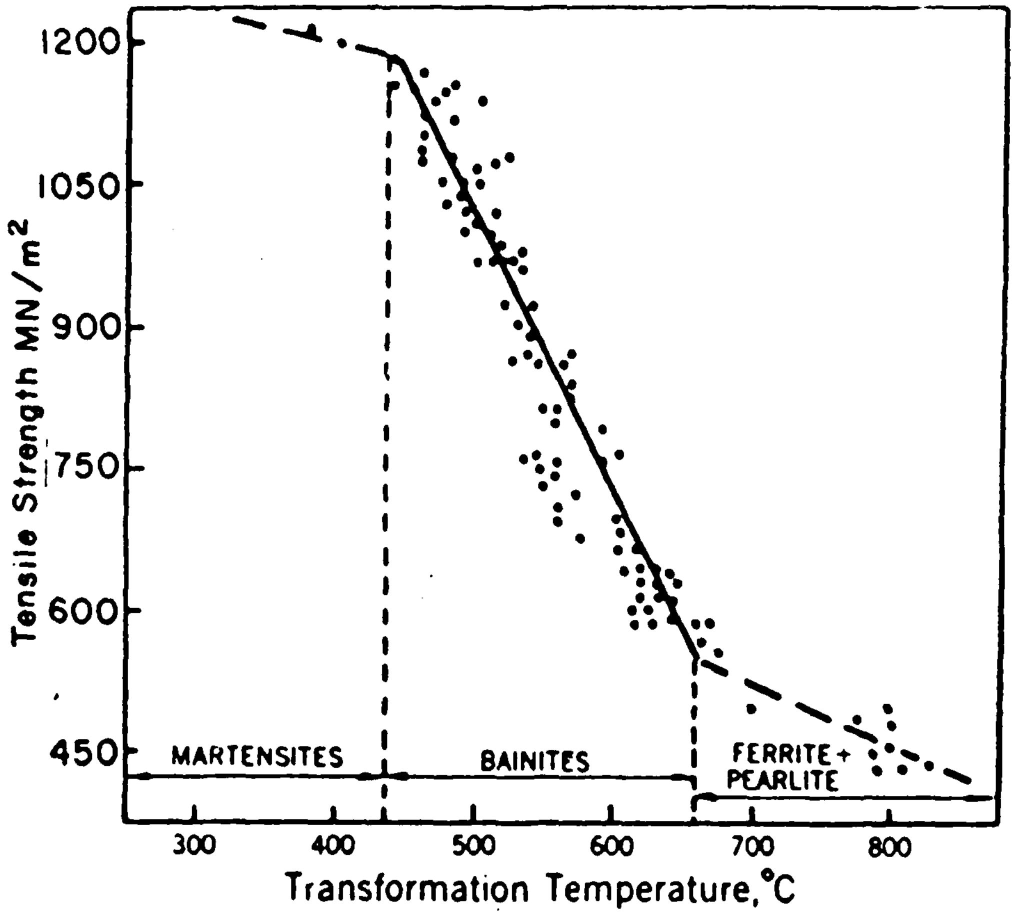

Figure 1: Relationship between 50% transformation temperature and tensile strength [4]

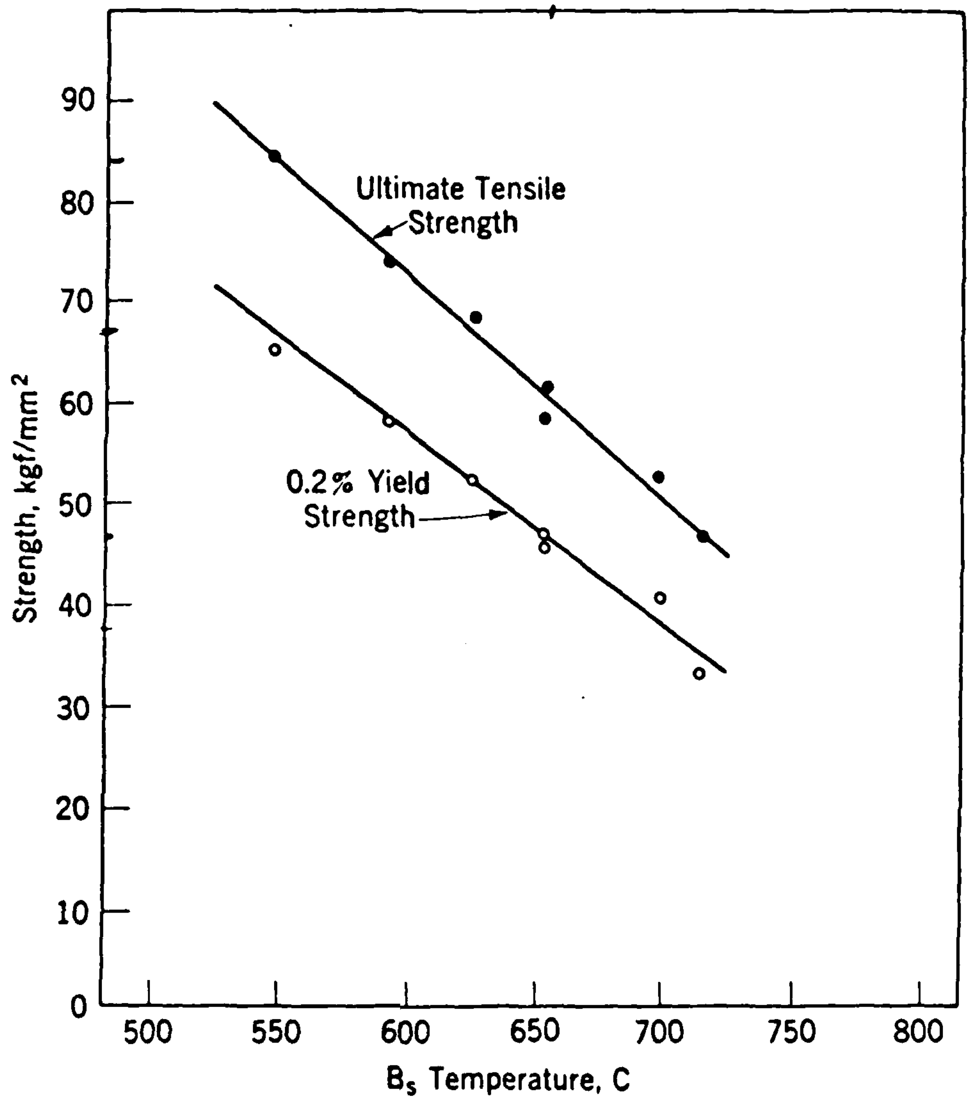

Figure 2: Relationship between B_S temperature and strength of molybdenum-boron bainitic steels with 0.1%C continuously cooled at 3.3 to 20°C/sec [5]

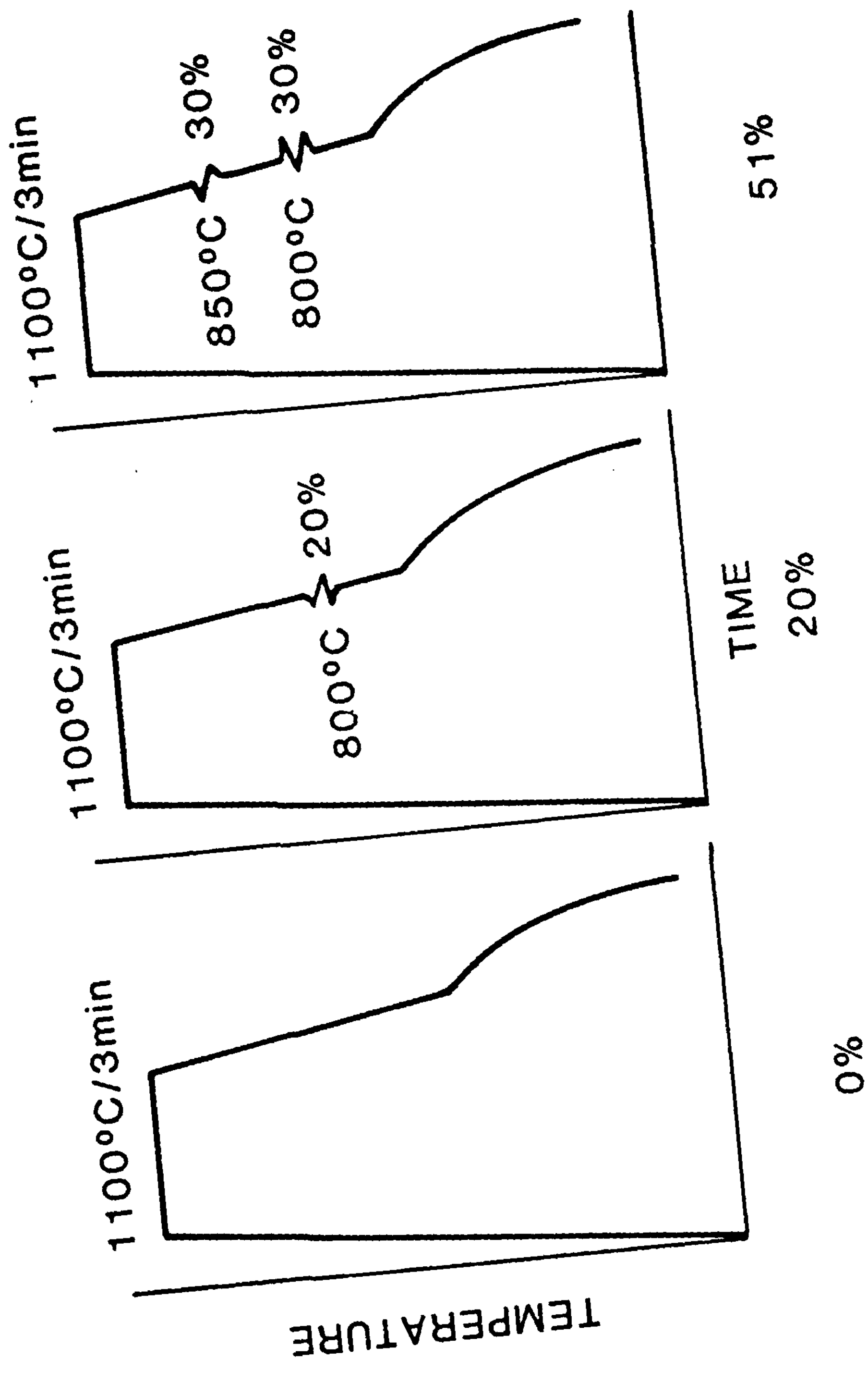

Figure 3: Schedule of thermomechanical treatment of austenite

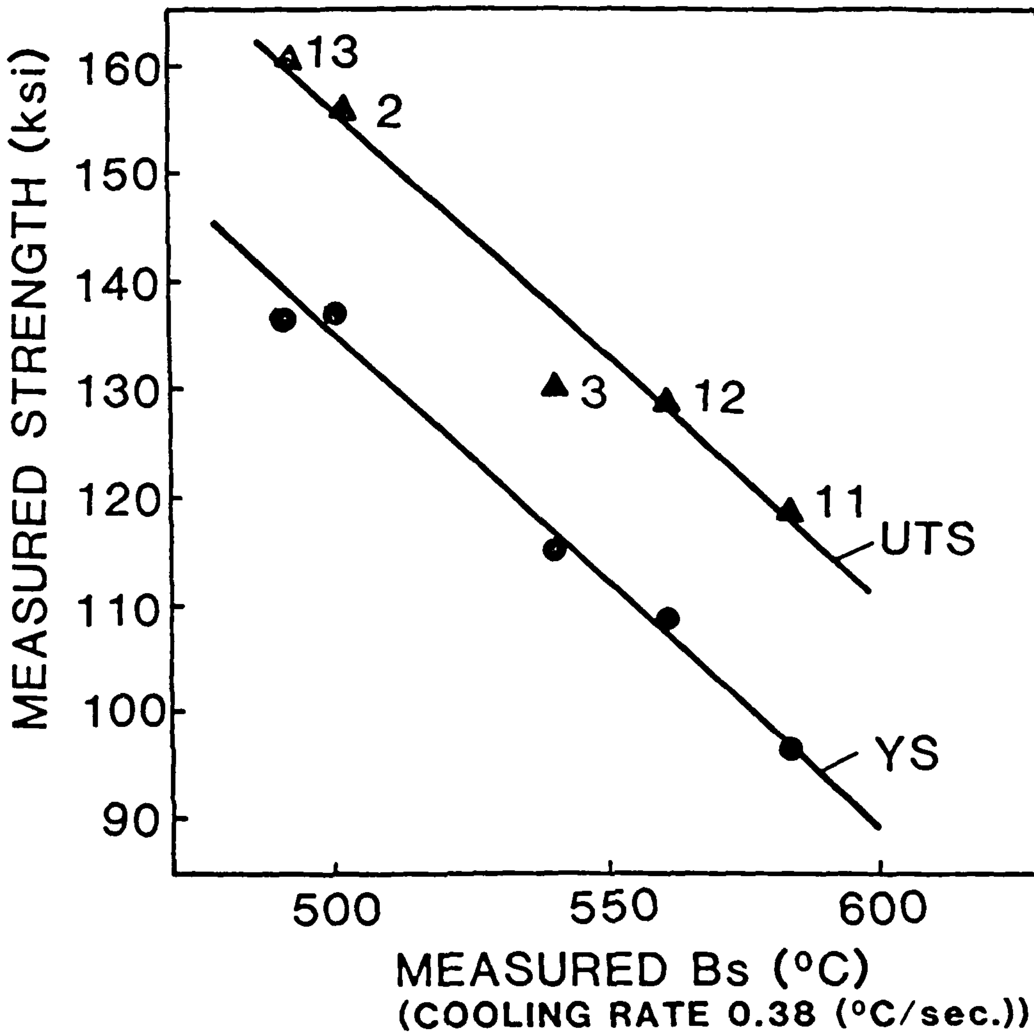

Figure 4: Effect of B_s temperature on strength of ultra low carbon bainitic steels

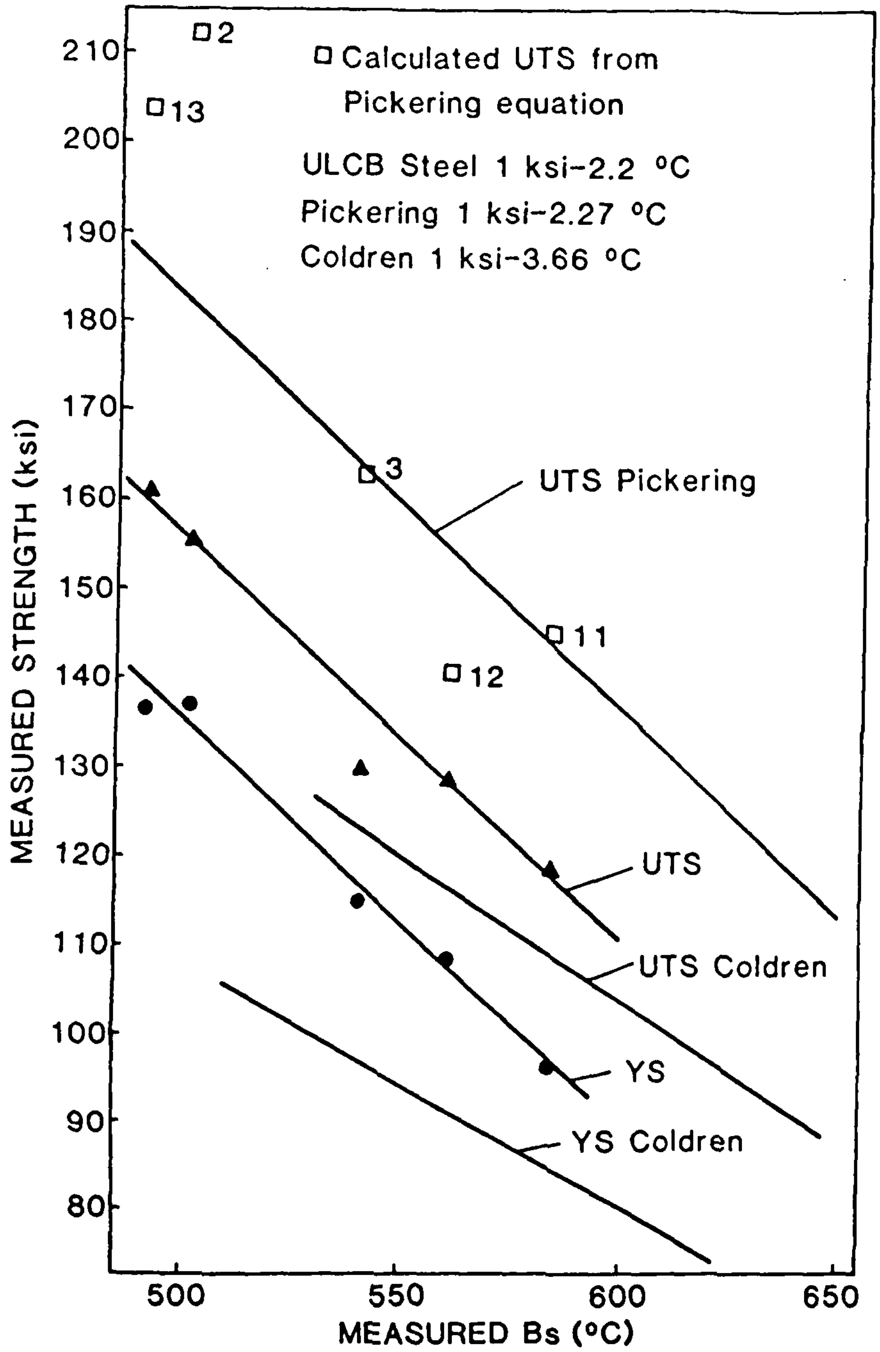

Figure 5: Comparison of B_S temperature and strength for a wide range of bainitic steel compositions

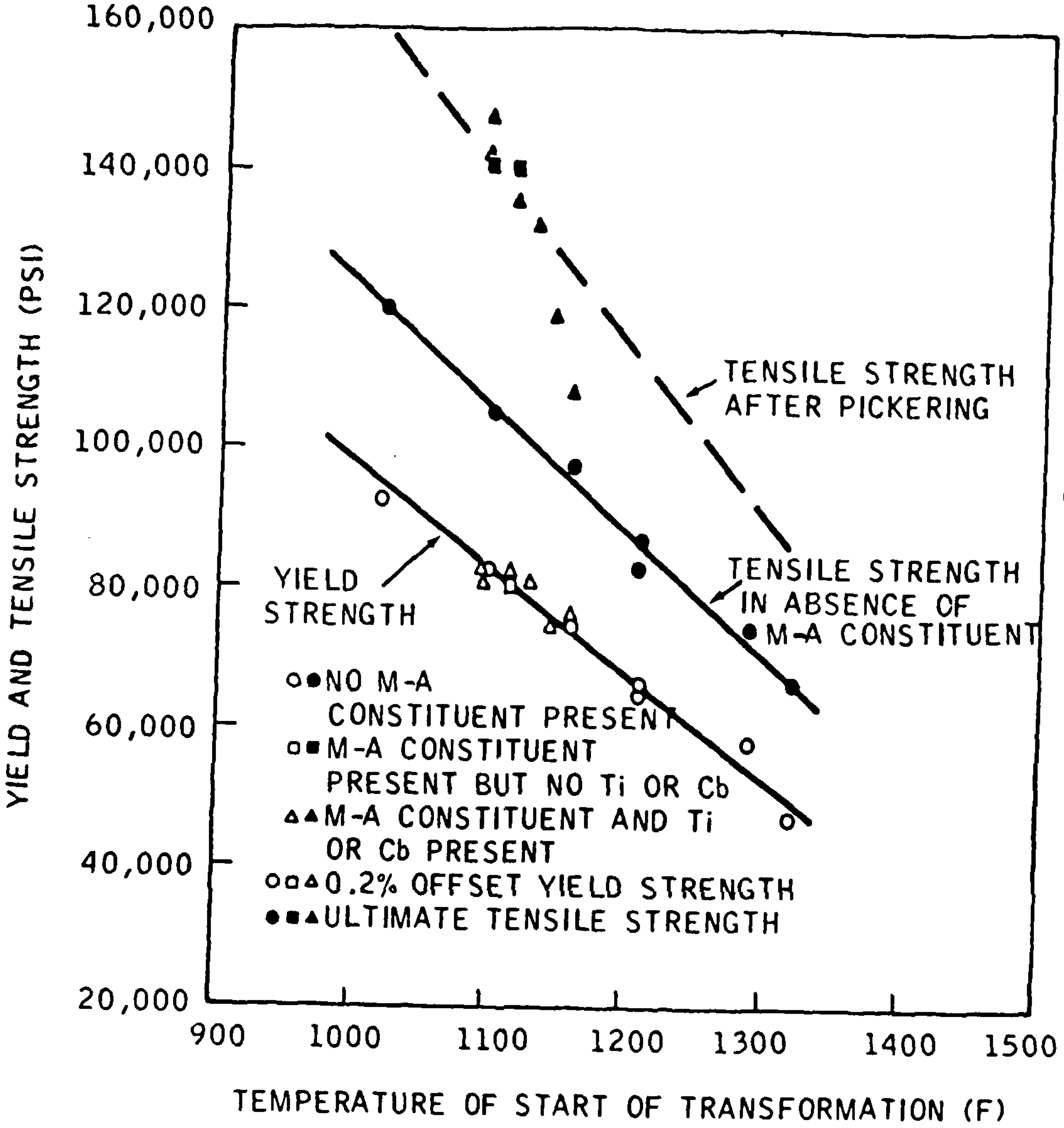

Figure 6: Relationship between strength and transformation temperature for some bainitic steels [6]

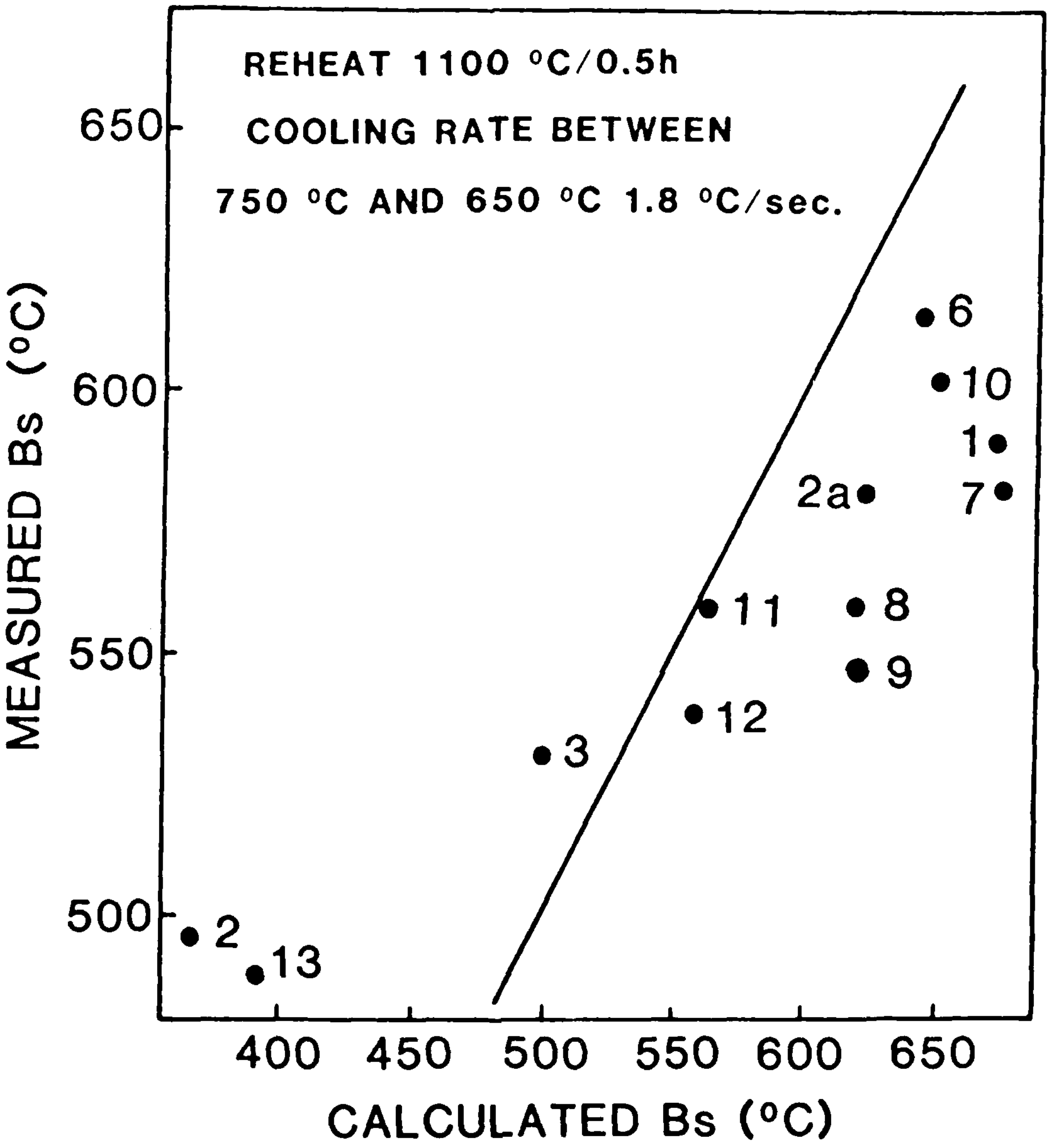

Figure 7: Relationship between measured and calculated Bs temperatures from investigated bainitic steels

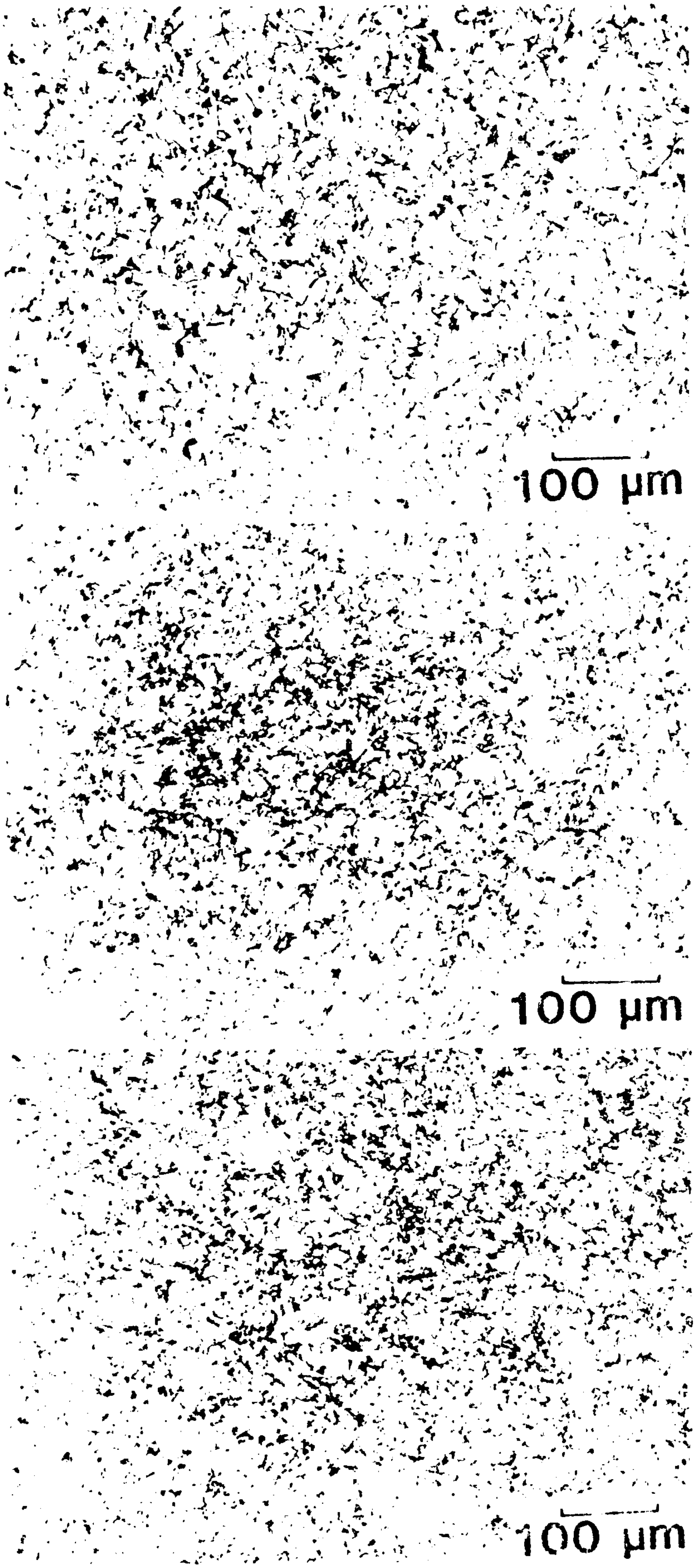

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Fig 8

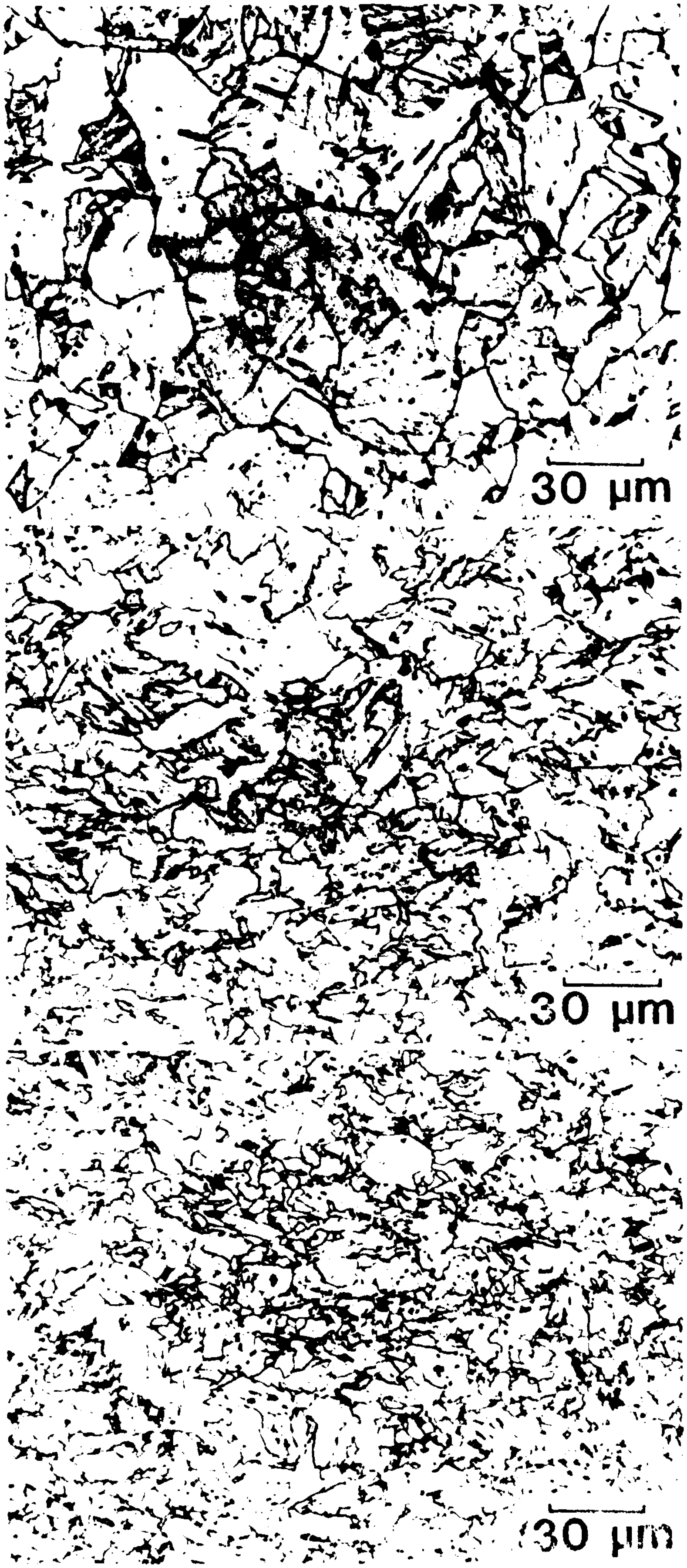

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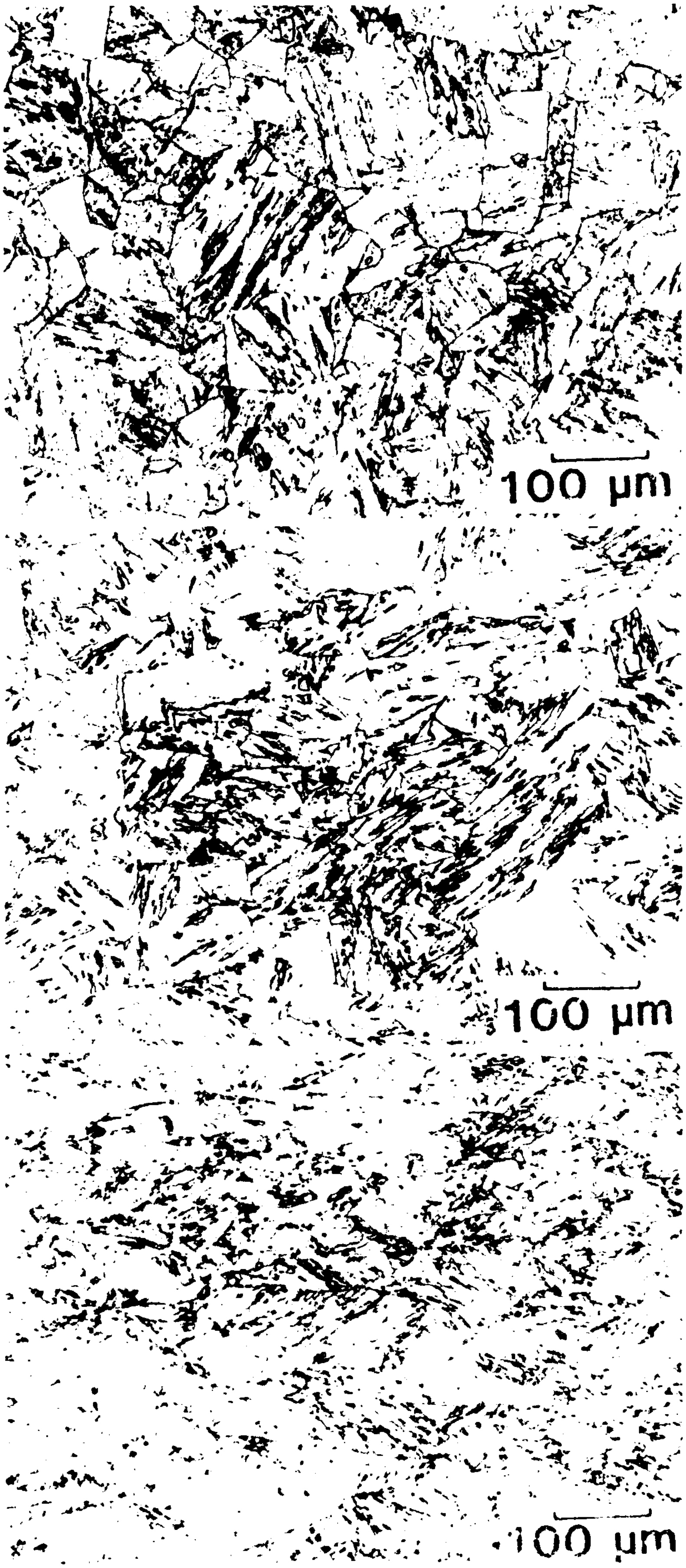
Fig 8



B1

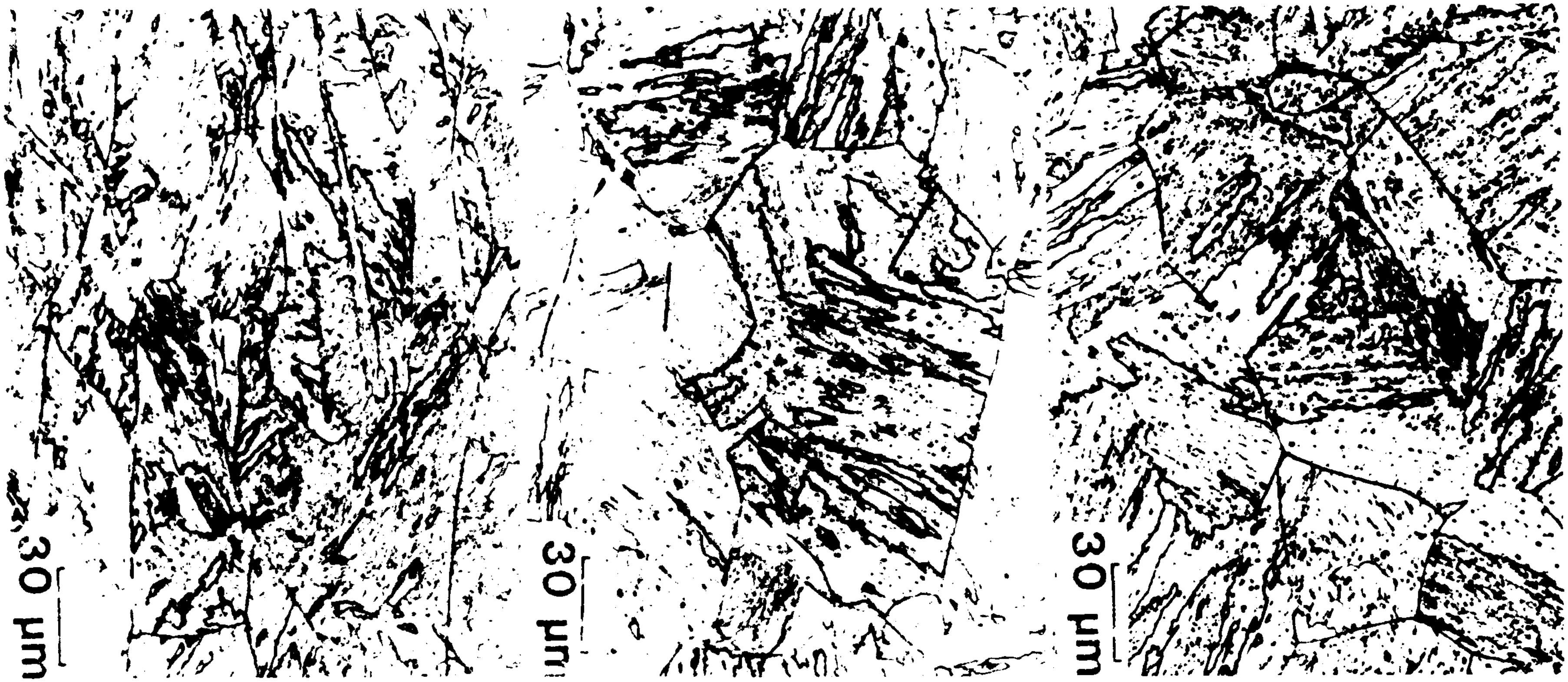
B2

B3

Fig 8

Fig 8. Microstructure of bainite formed from thermomechanically treated austenite

A - steel 6, B - steel 2; 1 and 4 - 0% deformation, 2 and 5 - 20% deformation, 3 and 6 - 51% deformation



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